Theoretical study of antiferromagnetism induced by paramagnetic pair-breaking in a strong-coupling superconducting phase(Digest_要約)

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Summary of thesis: Theoretical study of antiferromagnetism induced by paramagnetic pair-breaking in a strong-coupling superconducting phase

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Recently, enhancement of an antiferromagnetic (AFM) order or fluctuation in the high-field region of a superconducting (SC) phase have been observed in many d-wave superconductors with a strong paramagnetic pair-breaking (PPB) effect. In the heavy-fermion superconductor $CeCoIn_5$, a novel SC phase is realized in the high-field and low-temperature region of the SC phase. Experimentally, this high-field low-temperature (HFLT) phase has been suggested to be a coexistent phase of an incommensurate AFM order and a Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) SC order, where the SC order parameter is spatially modulated because of a strong PPB effect. It has also been found that the AFM order is present only in the HFLT phase but not present in the high-field normal phase, suggesting that an AFM order is more easily realized in the *superconducting* HFLT phase than in the normal phase. This is contradictory to the conventional view that an AFM order is competitive to a SC order and tends to be suppressed in a SC state. An AFM order existing near the SC transition field $H_{c2}(0)$ has been observed also in pressurized $CeRhIn_5$. Moreover, a field-induced AFM quantum critical point (QCP) located at a field slightly lower than $H_{c2}(0)$ has been suggested in many d-wave superconductors with a strong PPB effect, such as $CeCoIn_5$, $CeRhIn_5$, Ce_2PdIn_8, and $NpPd_5Al_2$. This implies that the AFM critical fluctuation is enhanced in the high-field SC phase near $H_{c2}(0)$.

In our previous study, it has been shown that the mechanism of the PPB-induced AFM ordering can explain the above-mentioned experimental results. A theoretical analysis based on the weak-coupling BCS model has shown that, in $d_{x^2-y^2}$-wave superconductors with a strong PPB effect, AFM ordering is enhanced in the high-field region of the SC phase, and the resulting AFM modulation vector is parallel to the gap node of the $d_{x^2-y^2}$-wave pairing function. This mechanism can explain the AFM ordering near $H_{c2}(0)$ in $CeRhIn_5$ and the field-induced AFM-QCP located at a field slightly below $H_{c2}(0)$. Furthermore, it has been found that the AFM ordering is even more enhanced by the Larkin- Ovchinnikov (LO)-type modulation of the SC order parameter. The AFM order existing only in the HFLT phase of

$CeCoIn_5$ can be understood from this result.

Although the above analysis is based on the weak-coupling model, where electron correlation is assumed to be weak, most of SC phases with a strong PPB effect are realized in unconventional superconductors where electron correlation is strong. Furthermore, as mentioned above, many d-wave superconductors with a strong PPB effect are close to an AFM-QCP, suggesting that the AFM critical fluctuation, which is ignored in the weak-coupling model, can affect the AFM ordering. Therefore, it is necessary to extend the theory of the PPB-induced AFM ordering to a strong-coupling model including the effect of the AFM fluctuation.

In this thesis, we study the PPB-induced AFM ordering in a strong-coupling SC state by investigating the two-dimensional Hubbard model with the Zeeman energy using the fluctuation-exchange (FLEX) approximation. We calculate the transverse AFM susceptibility and show that the PPB-induced AFM ordering can be realized in a strong-coupling SC state, and its mechanism is essentially the same as that in the weak-coupling model. Moreover, a first-order SC transition, which has been shown to be realized in a SC state with strong PPB in the weak-coupling model, is studied in the strong-coupling model. It is shown that a first-order SC transition is realized in the strong-coupling model, although the first-order $H_{c2}(T)$ is suppressed at low temperatures by the too strong PPB effect in this model.

Next, we investigate the influence of the strong-coupling effects on the PPB-induced AFM ordering in the situation close to an AFM-QCP. We show that the PPB-induced AFM ordering is affected mainly by the following three effects: the quasiparticle renormalization (i.e. the mass enhancement), the amplitude of the SC order parameter, and the Stoner enhancement in the normal state. On approaching the AFM-QCP, the quasiparticle renormalization suppress the AFM ordering, whereas the large SC order parameter induced by a strong pairing interaction enhances it. From the dependence of the AFM ordering on the microscopic parameters, however, we find that promotion of the PPB-induced AFM ordering owing to the Stoner enhancement is dominant over the other two effects near an AFM-QCP. Therefore, the AFM order existing only in the high-field region of the SC phase is expected to be realized in d-wave superconductors with a strong PPB effect close to an AFM-QCP.